Science on the Fly

Autonomous Science for Rover Traverse

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Preview

Motivation and Objectives

Technology Research

Field Validation

Science Autonomy

Science Autonomy is NOT to replace scientists with robots

Science Autonomy is to improve the quality and quantity of science data return from exploration missions

Motivation for Science Autonomy

Exploration methods with all decision making on Earth are increasingly difficult to sustain

Factors motivating greater autonomy:

- **Mission duration**
- **Operations costs**
- **Instrument placement and operation**
- **Verifying observations**
- **Sampling and drilling control**
- **Command complexity/contingencies**
- **Communication bandwidth and data volume**

Science Autonomy Motivation

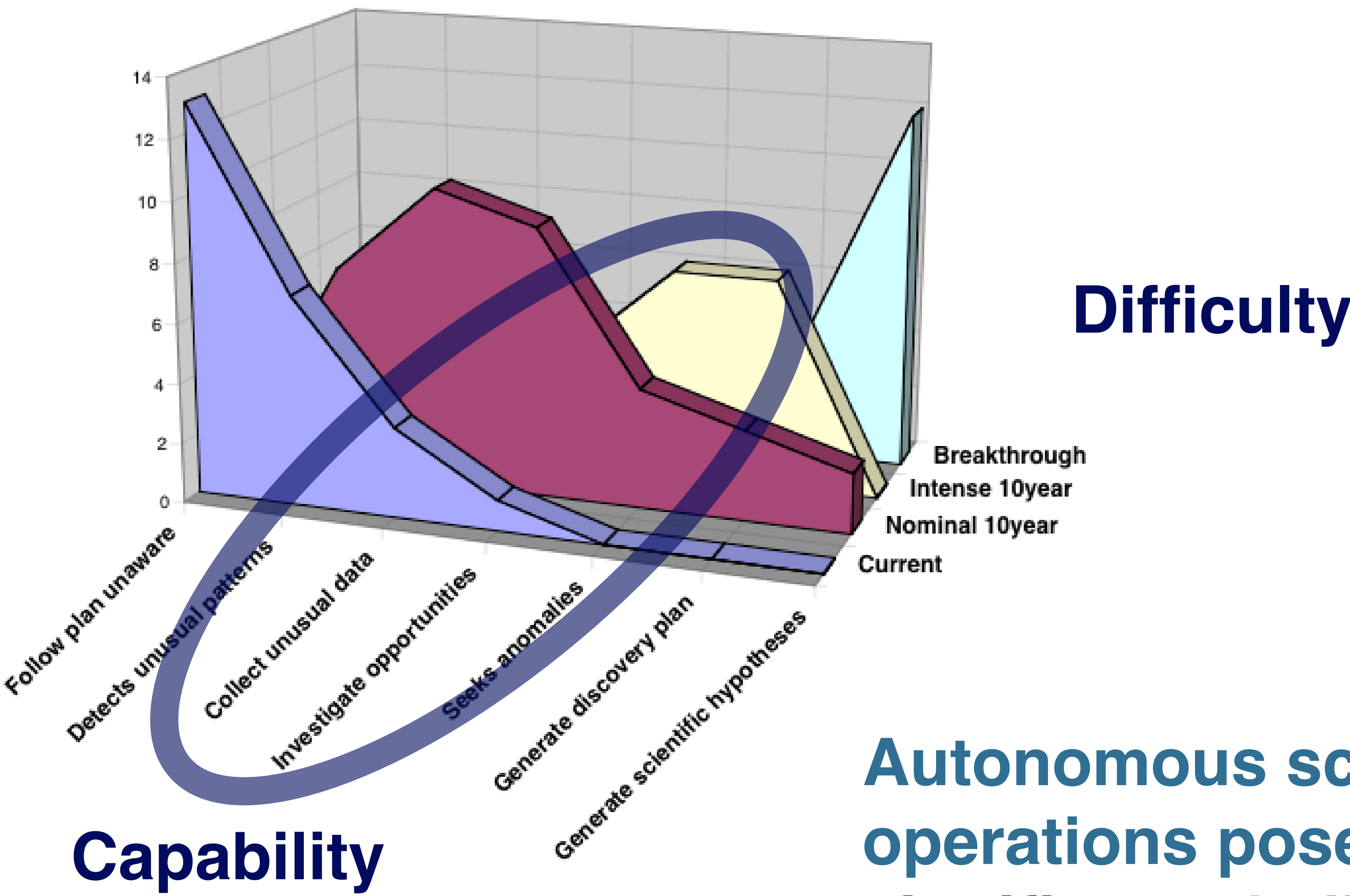
NEXT Space Robotics Study

Assessment the current and projected state-of-the-art in space robotics including surface exploration

Challenges relative to science autonomy:

Minor	Moderate	Major
Obstacle Detection	Map Building	Localization
Obstacle Avoidance	Health Monitoring	Terrain Detection
Path Execution	Path Planning	Mission Planning
Coverage Planning	Resource Planning	Exploration Planning
		Science Data Understanding

Science Autonomy



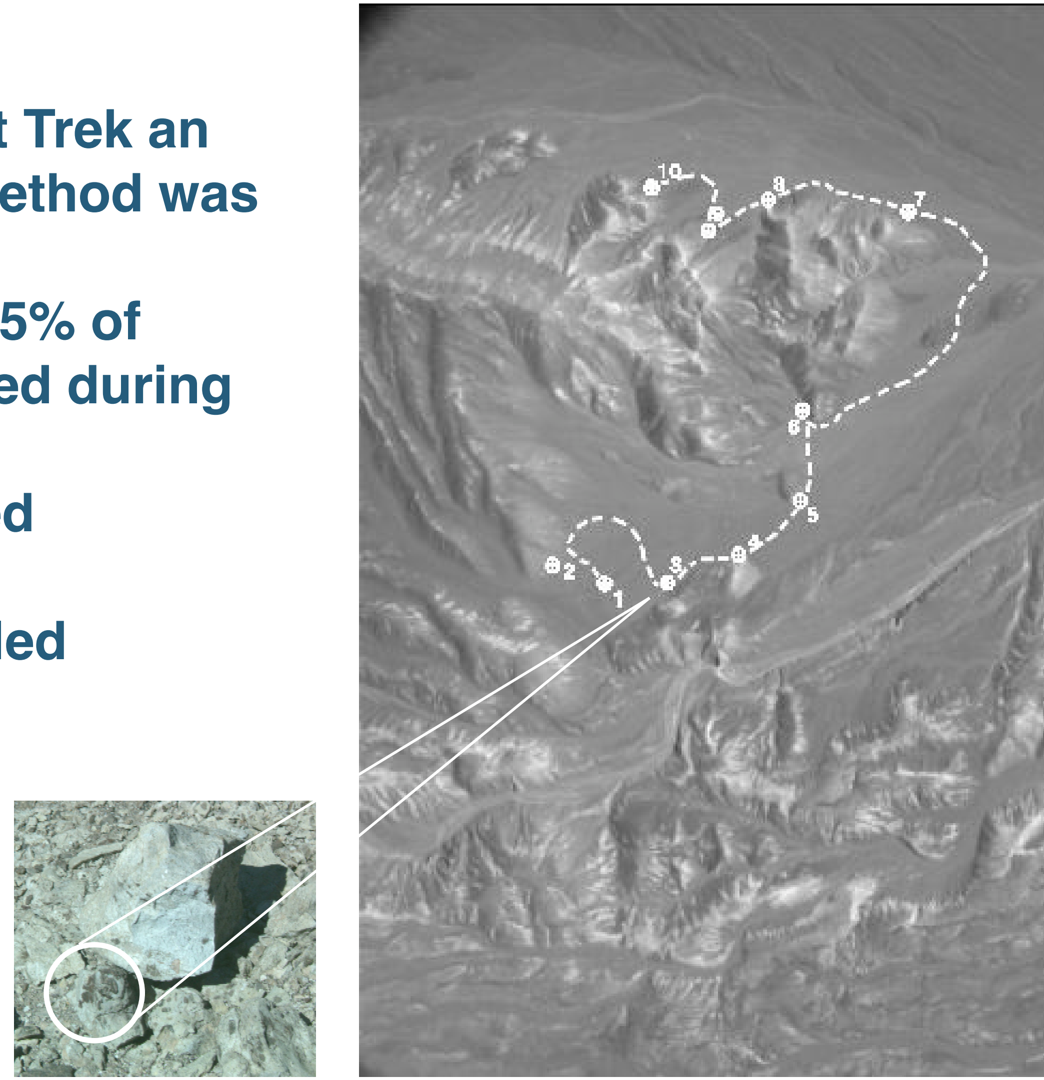
Autonomous science operations pose significant challenges

Science on the Fly Motivation

Geology on the Fly

During 1997 Atacama Desert Trek an experiment in exploration method was conducted:

- Maintain rover in motion 75% of the time (science conducted during traverse)
- Traverse 1.5km (supervised teleoperation)
- Pause at 10 sites for detailed observation



Outcrop with fossilized stromatolite detected

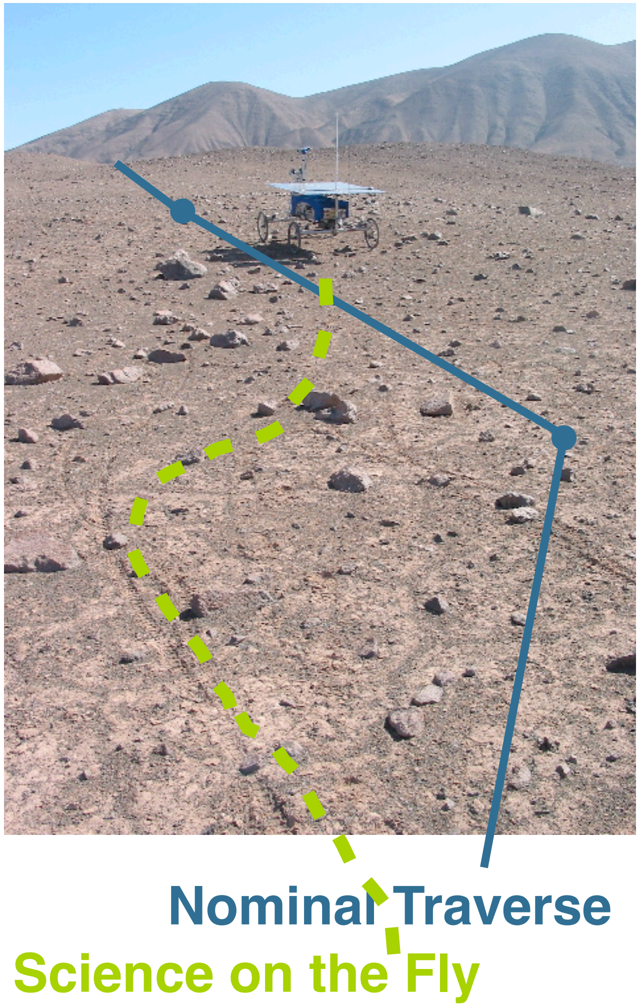
Science on the Fly

Science autonomy during rover traverse

Research:

- **Feature detection (similar, dissimilar, and unique)**
- **Feature classification and evaluation (significance)**
- **Science-informed exploration**
- **Science autonomy architecture**

Focus on developing techniques and validating in ground-truthed rover experiments



On-the-Fly Observations

Feature Detection and Classification

Rocks and soils

- Size, color (white rocks), roundness, sphericity, mineral composition (carbonates), spectra, fluorescence(chlorophyll signature), etc.
- Similarity, dissimilarity, uniqueness

Regions

- Texture, color distribution, size distribution, statistical measures, etc.
- Boundary localization

Rock Detection Example

Scene Image

Difference Operator

Threshold

Smoothing Operator

Segmentation

Rocks

Illustrative example not necessarily an effective algorithm

Region Segmentation Example

Technical Approach and Metrics

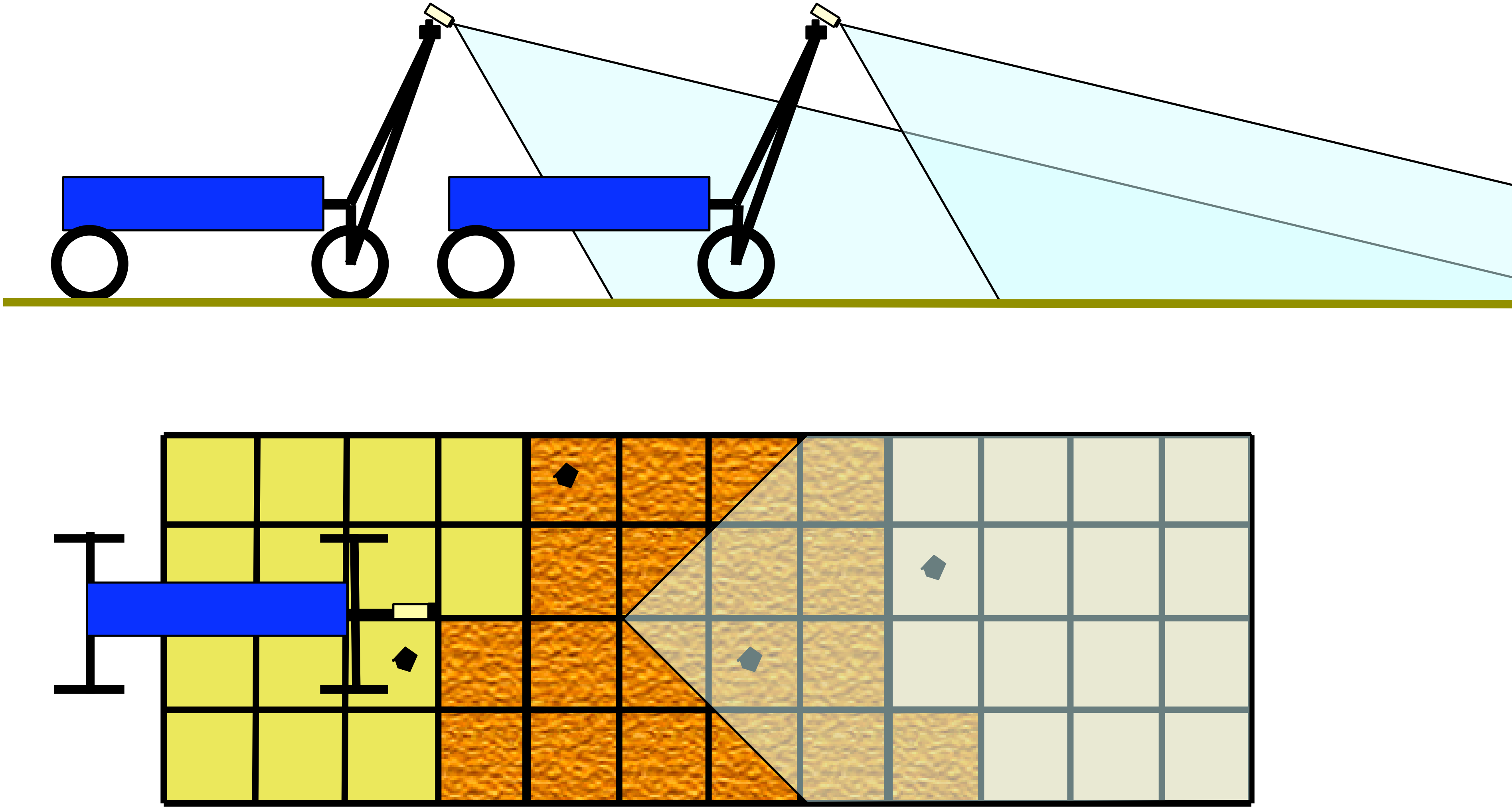
Feature Detection

- Implement several candidate algorithms
- Apply each algorithm to image set
- Analyze detection performance (rate and errors)

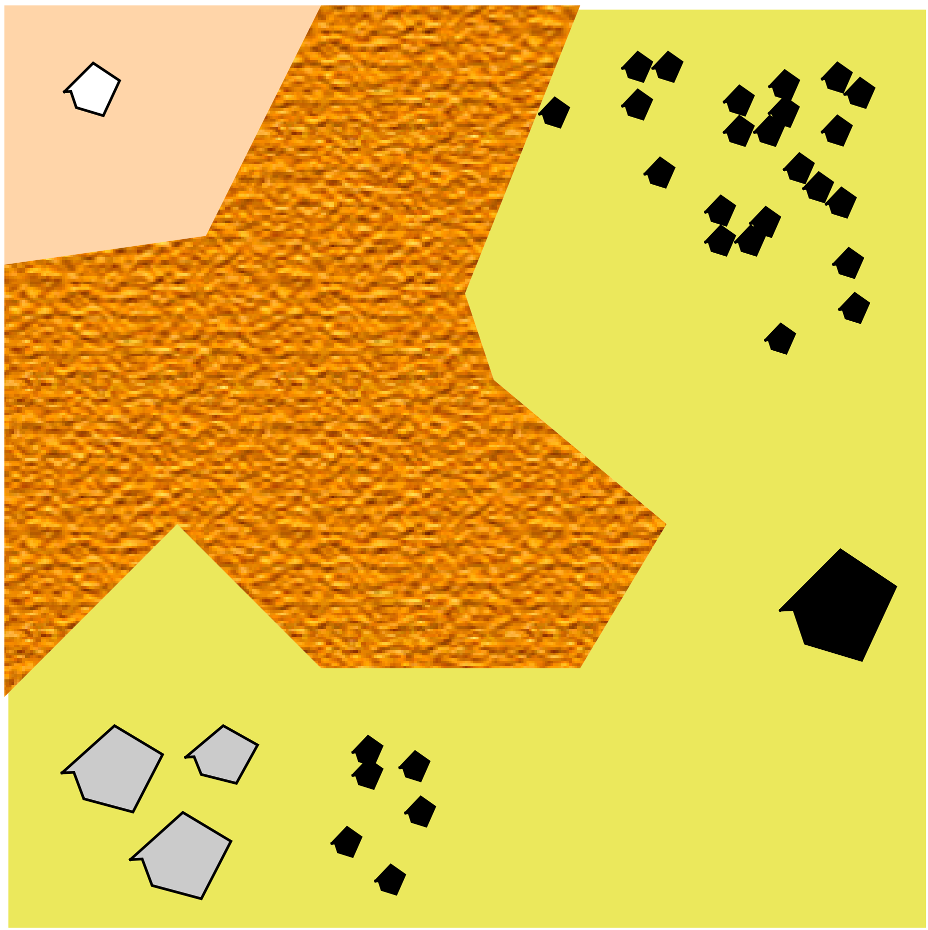
Feature Classification

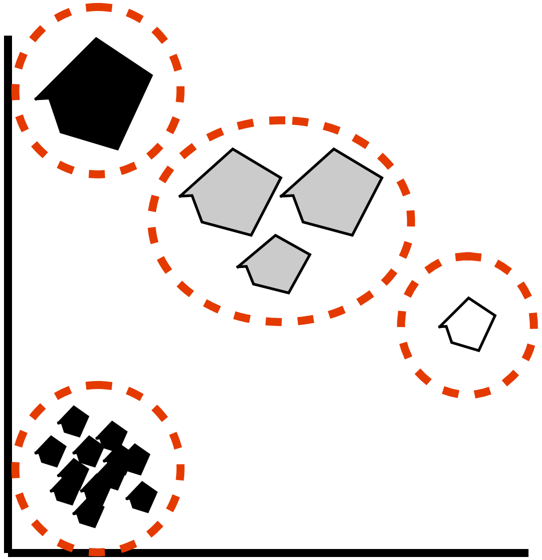
- Implement classification approach (Baysian)
- Apply to detected features
- Compare to manual classification

Science Observer

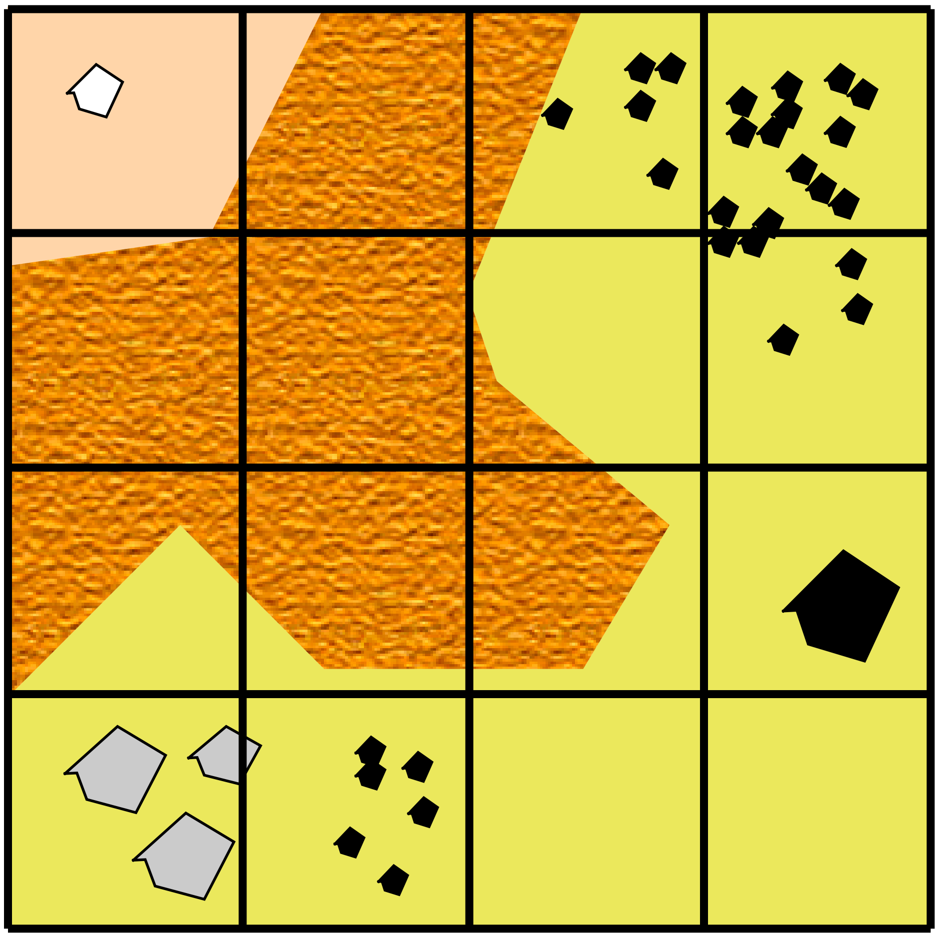


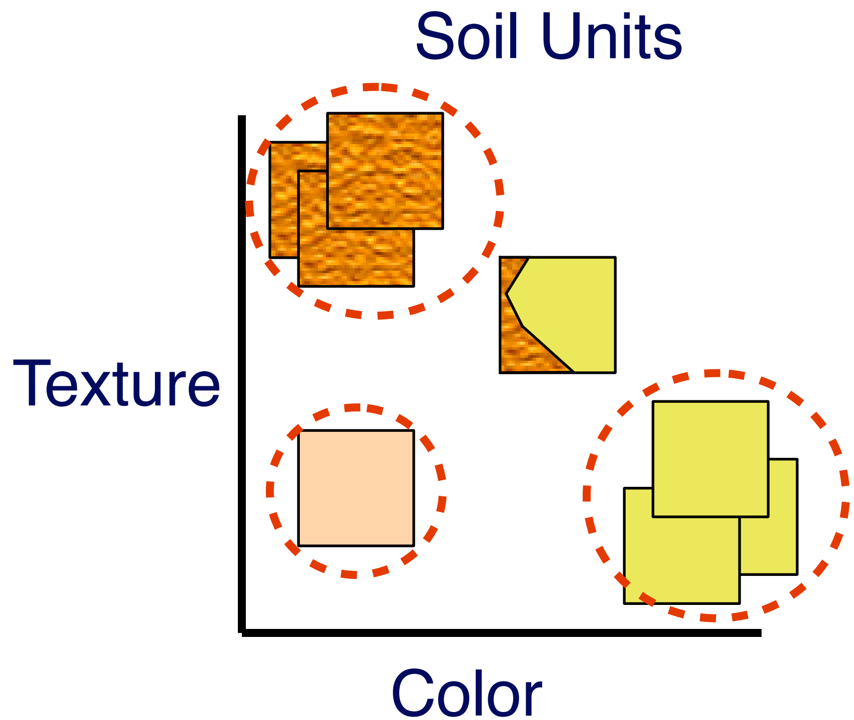
Observation Map - Rocks



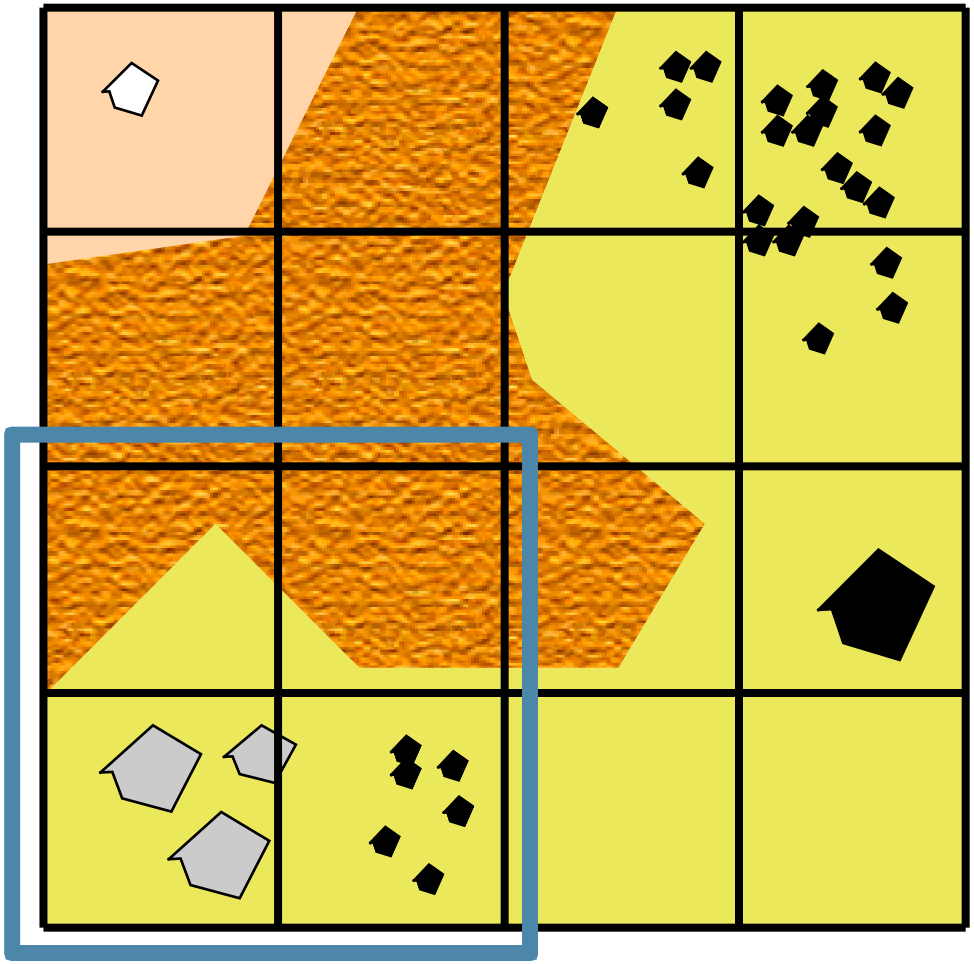


Observation Map - Soils



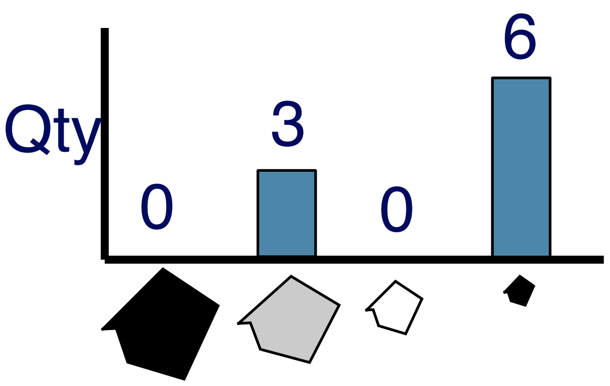


Observation Map - Regions

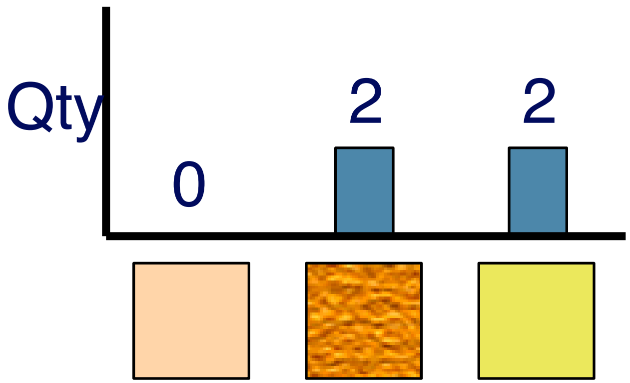


Region Characterization

Rock Distribution

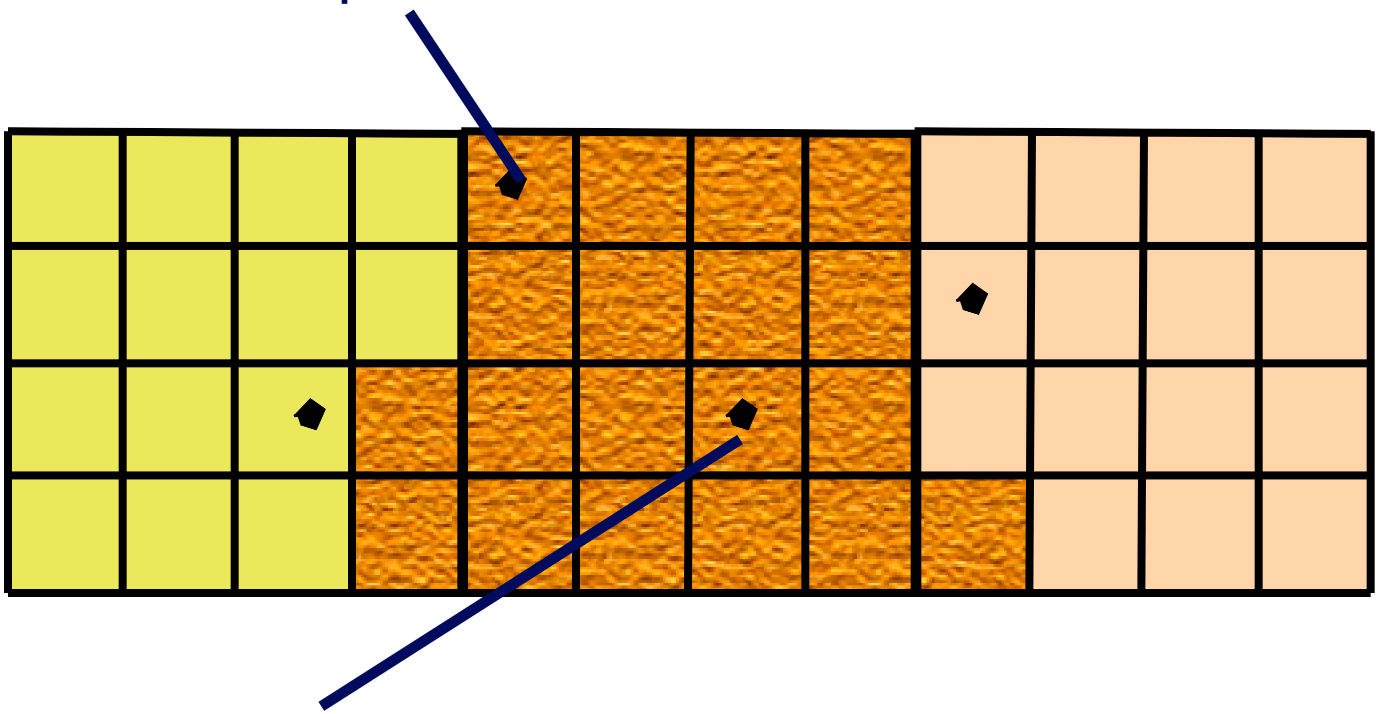


Soil Unit Distribution



On-the-Fly Planning

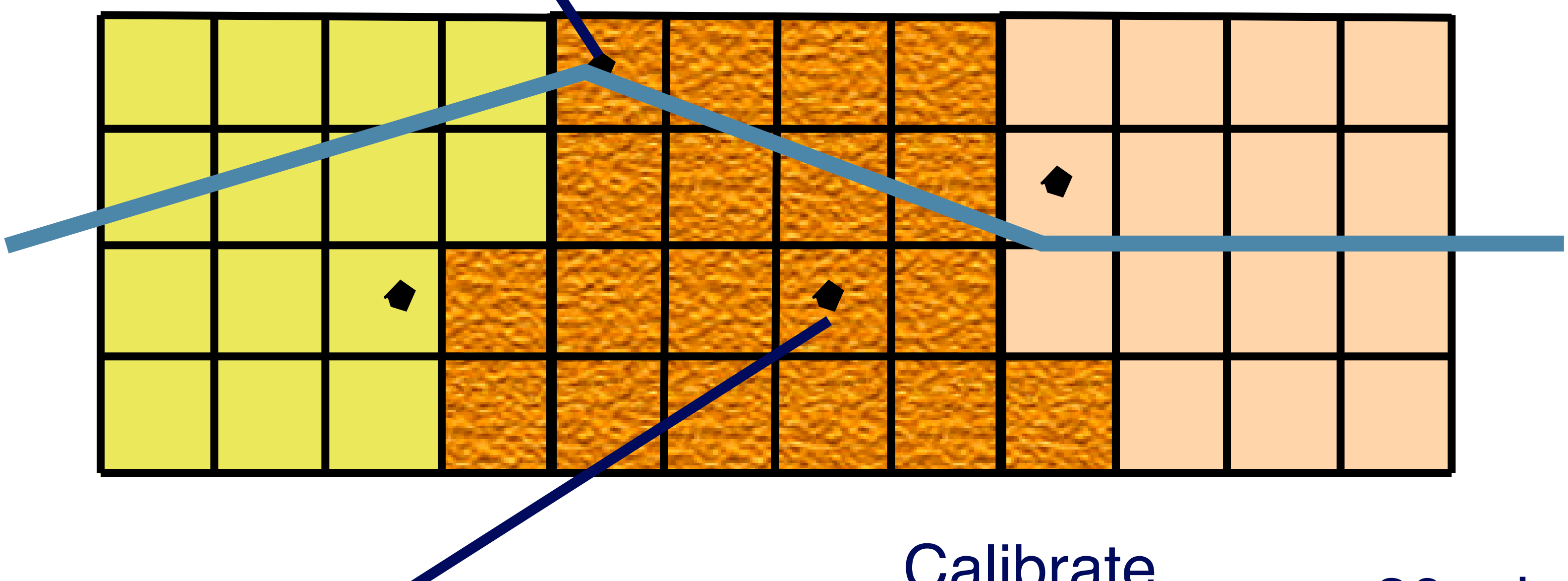
Spectra, 30



Fluorescence images, 100

Science Planner

Spectrum, 30 → Warm up, Calibrate, Take reading → 3 minutes, 2000 J

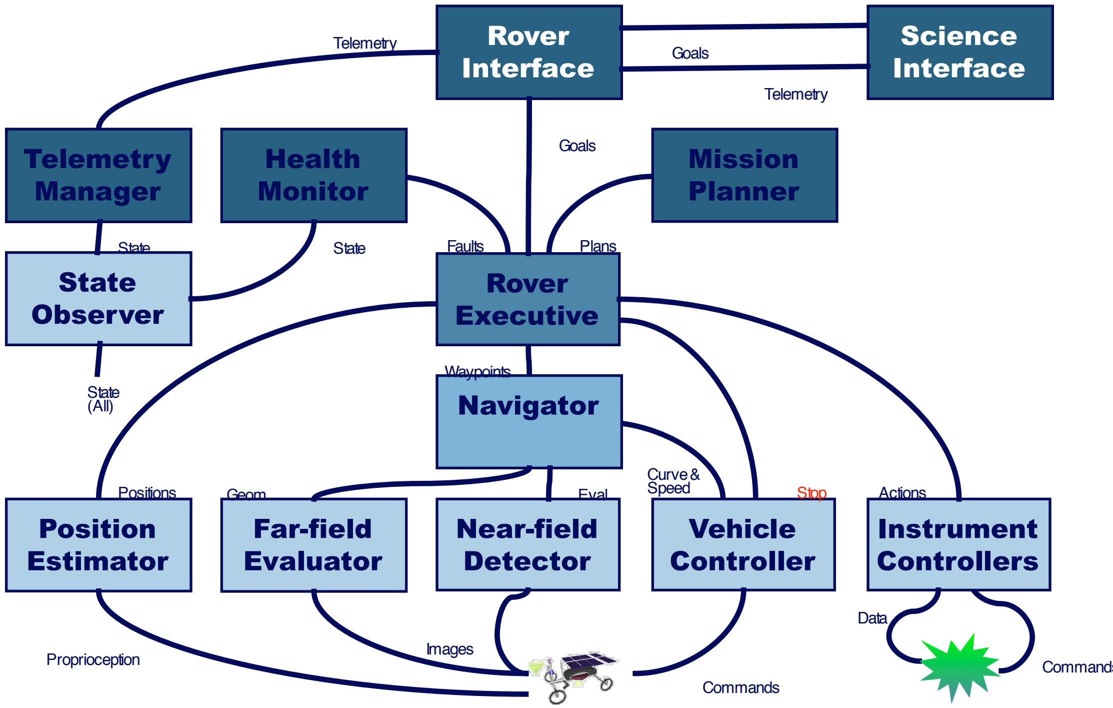


FI image set, 100 → Calibrate, Spray dyes, 7 channels → 30 minutes, 45,000 J

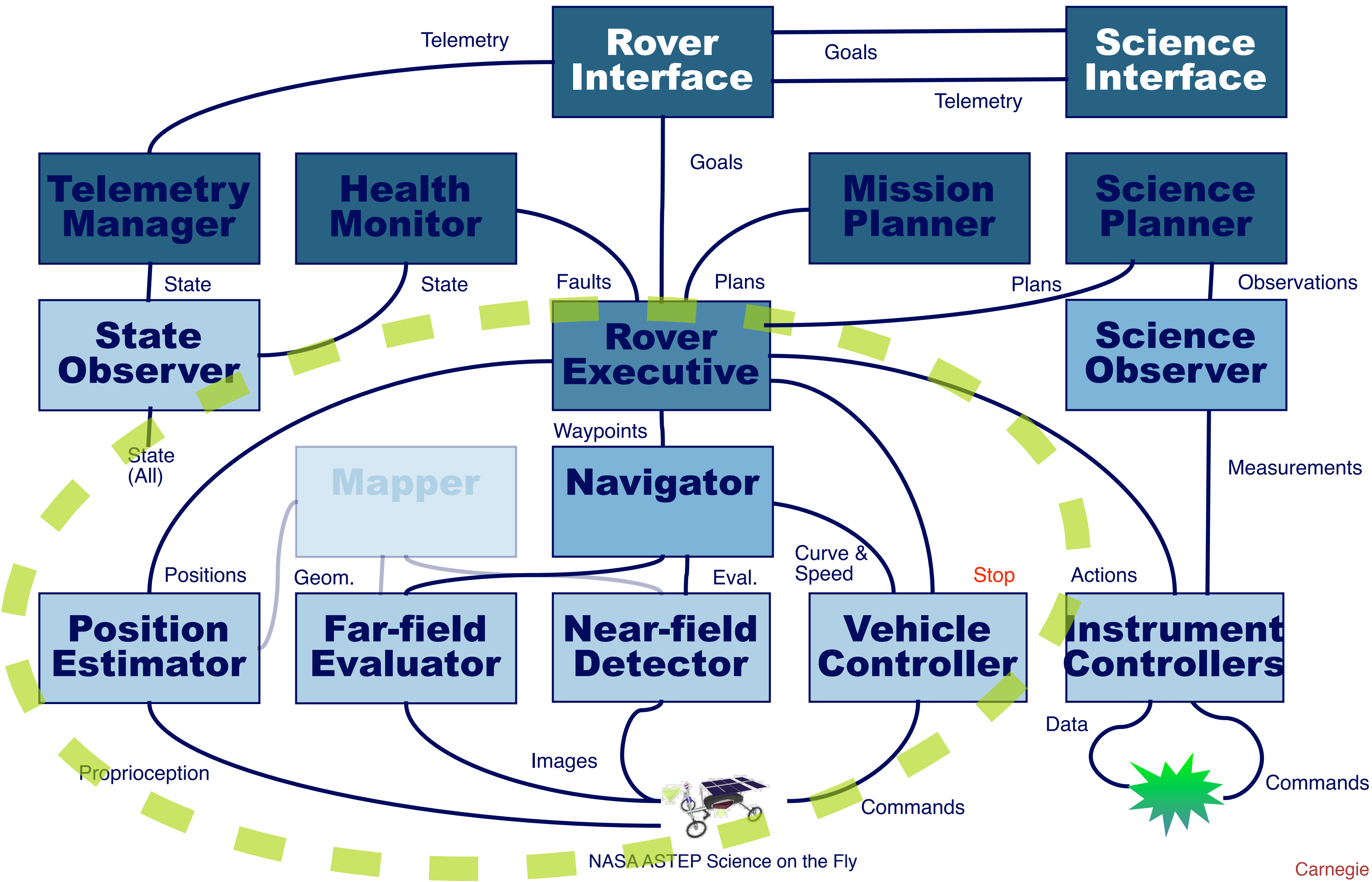
Science Autonomy Architecture

Deep Integration

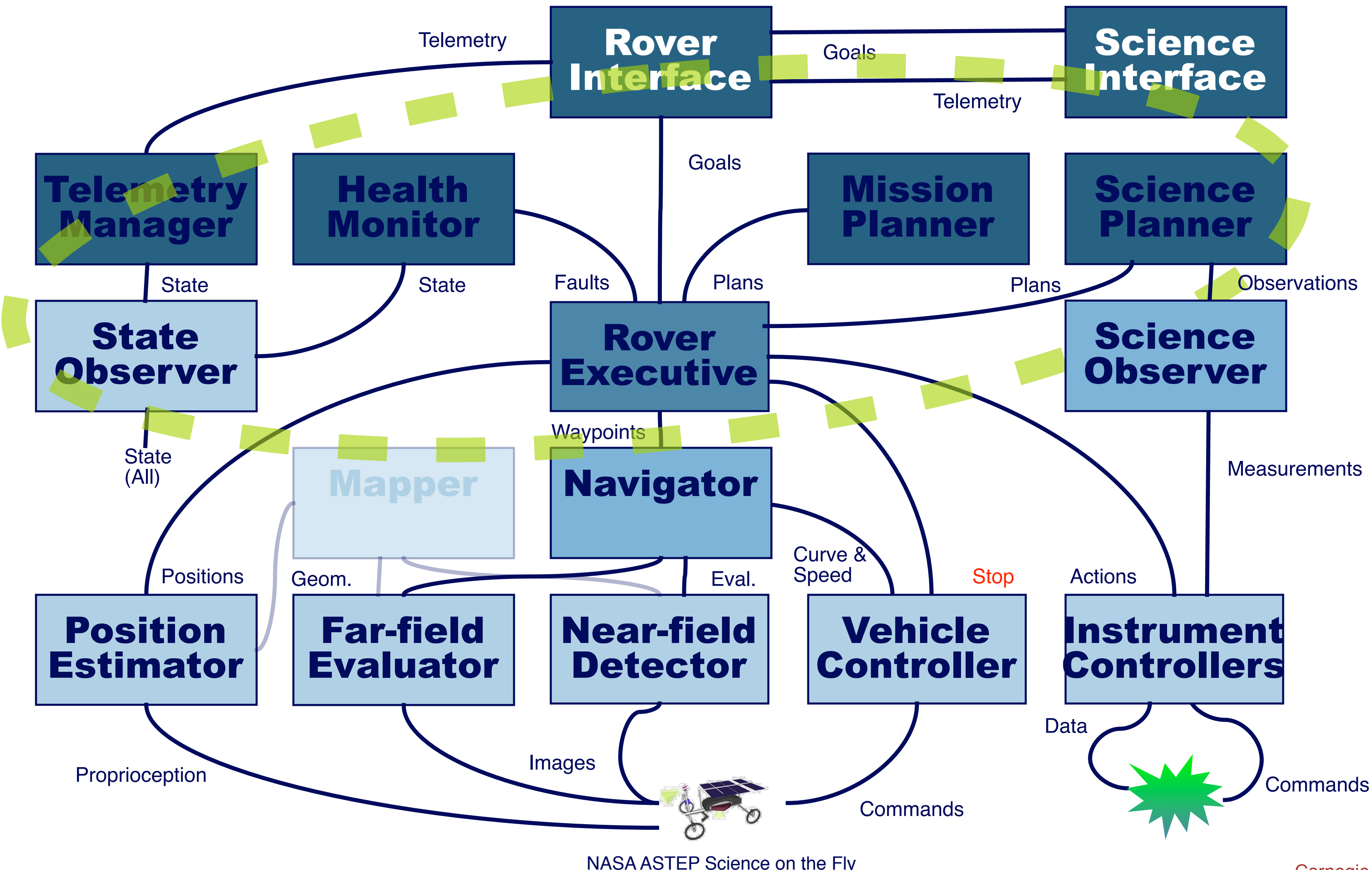
- Science observation is closely related to navigational observation and can be optimized
- Science planning is intimately related to planning for locomotion and resources



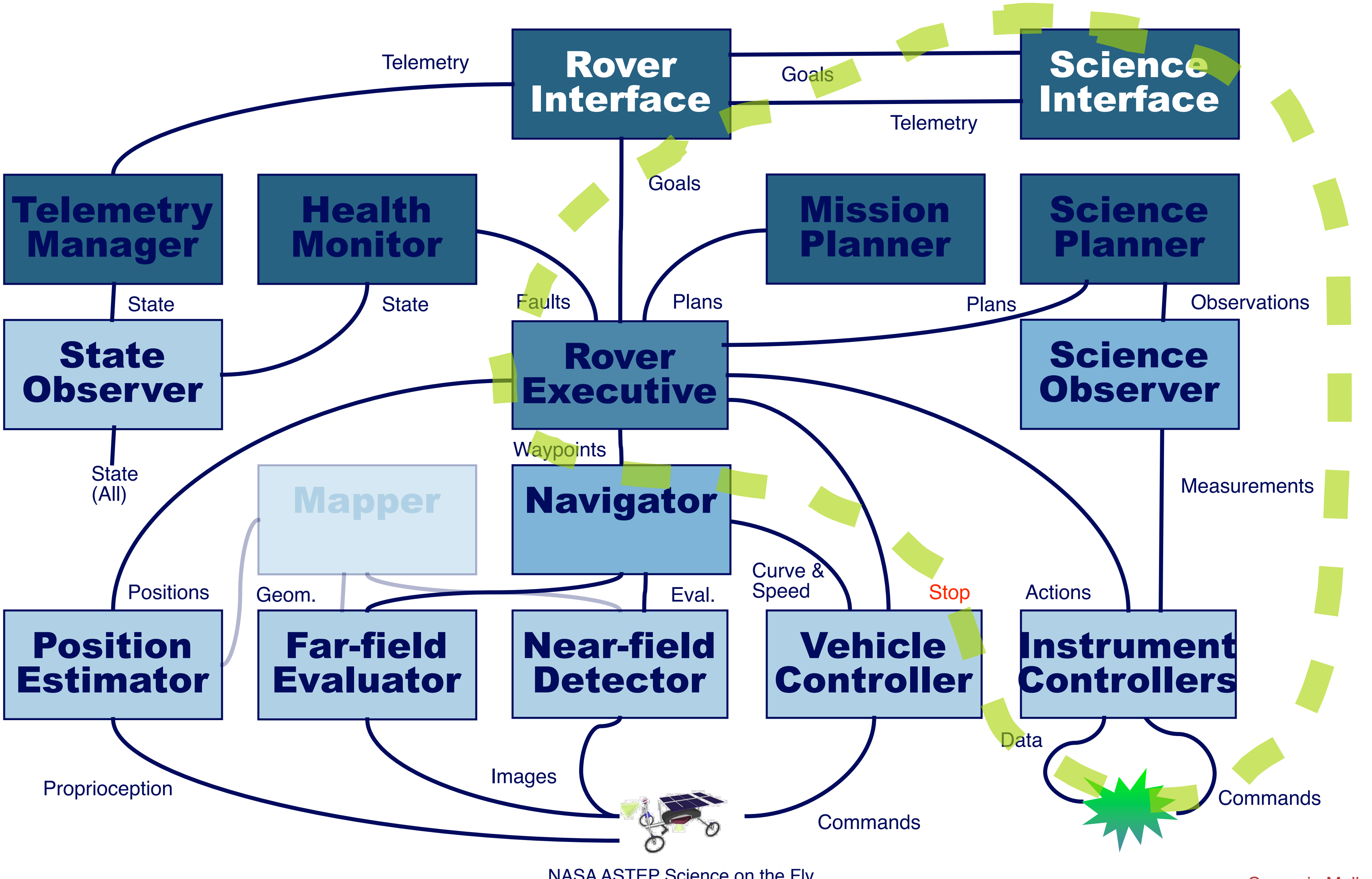
Architecture - Navigation



Architecture - Planning and Execution



Architecture - Science Autonomy

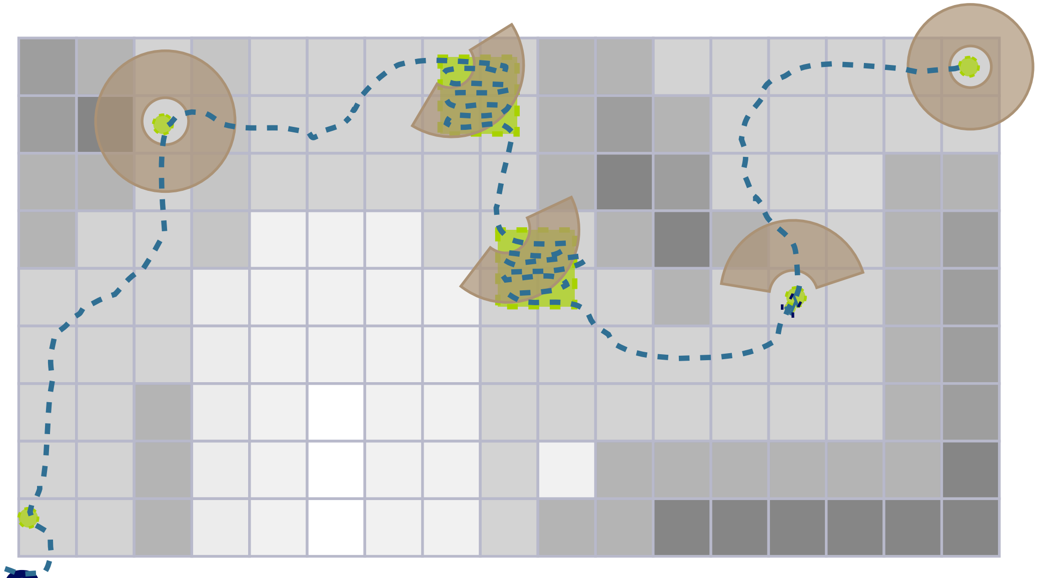


Validation and Verification

Two aspects:

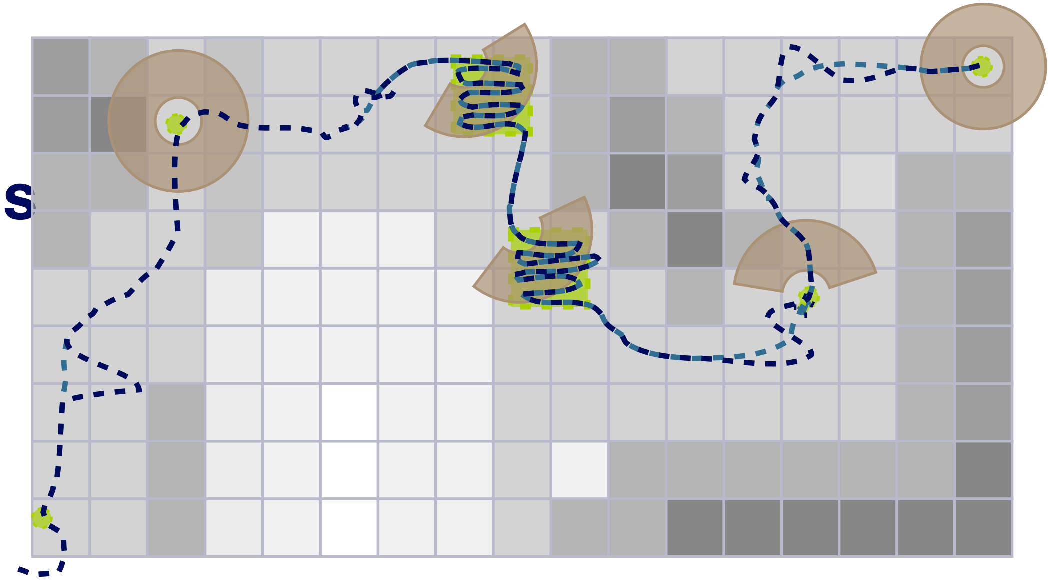
- **Validate detection and categorization perform correctly in the relevant domain**
- **Verify that science-on-the-fly observation and planning improves science productivity**
  - **Measured by comparison to control experiment with no science autonomy**
  - **Quantify of useful observations and quality of science interpretation**

Experimentation



- **Design rover traverse**
  - Following Atacama operations concept
  - Possibly cross geologic boundary
- **Complete science goals**
- **Observe environment and detect features**
- **Categorize features and compute statistics**
- **Compare automatic versus manual analysis (validate)**

Field Experimentation



Design rover traverse
Execute nominally and make science observations

Repeat path with Science Observer detecting and Science Planner functioning with the Mission Planner (to consider resources) and modifying path to collect additional data

Measure

- **Observations added**
- **Observations lost**
- **Observation quality (scientist analysis)**

Field Investigation

Formulate habitat hypotheses

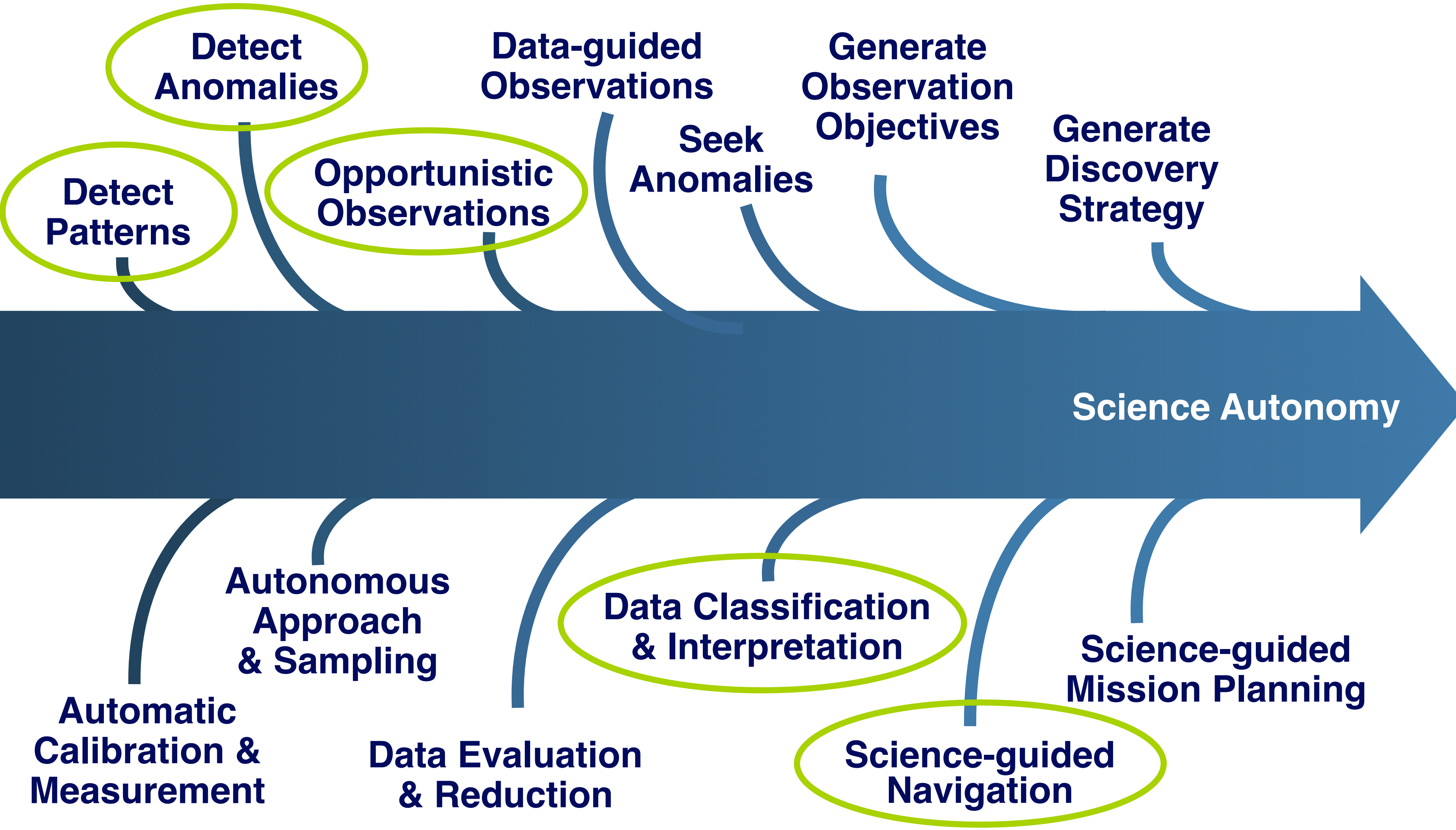
What constitutes a viable micro-habitat?

Important properties may include sunlight and radiation, slope exposures, wind, moisture, and geologic composition of rocks and sediments.

Identify distinguishing characteristics

Can rover autonomously survey habitats?

Developing S Science on the Fly



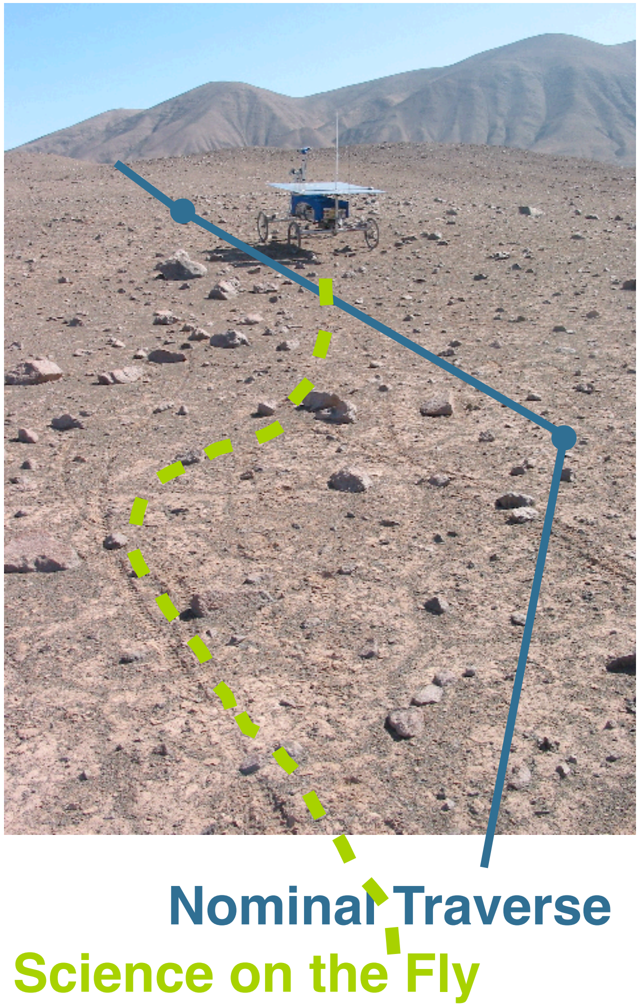
Science on the Fly

Science autonomy during rover traverse

Technology

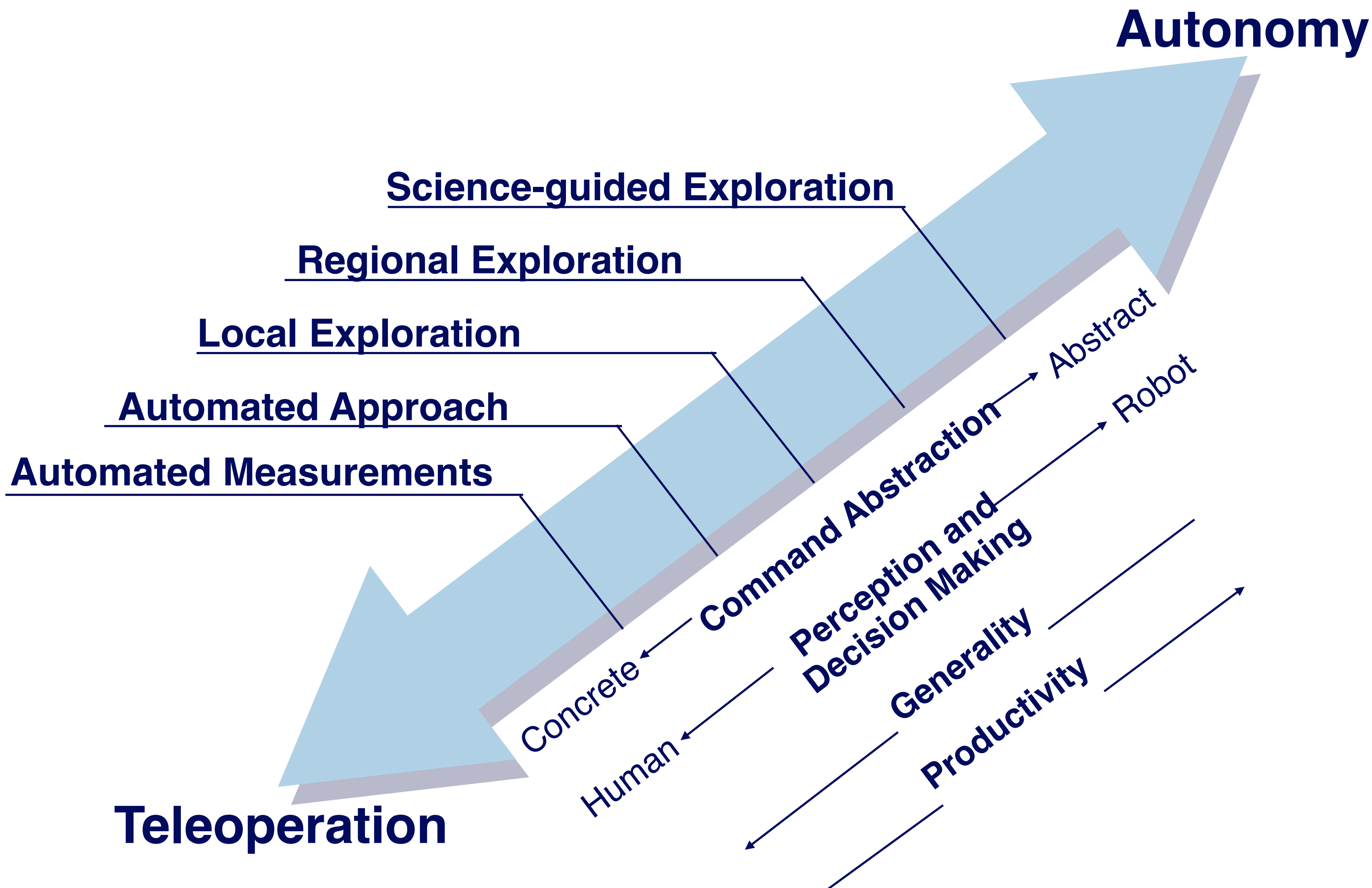
- **Feature detection**
- **Feature classification and evaluation**
- **Science-informed exploration**
- **Science autonomy architecture**

Focus on developing techniques and validating in field experiments



Extra Motivation

Improving Productivity



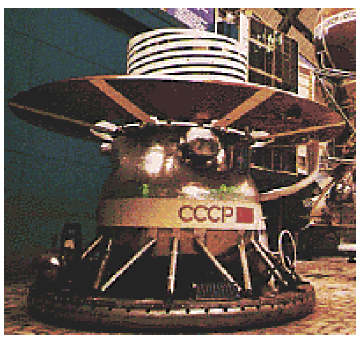
Growing Science Data Volume

Focused Science Missions

Focused Investigation

Single Measurements

Flybys and Landers



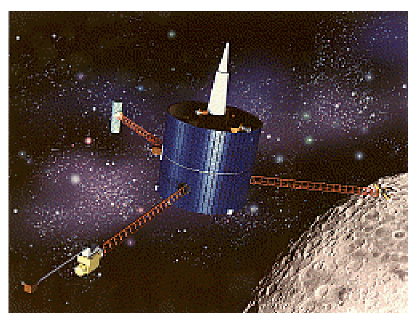
Venera Lander

Discovery Science Missions

Broad Investigation

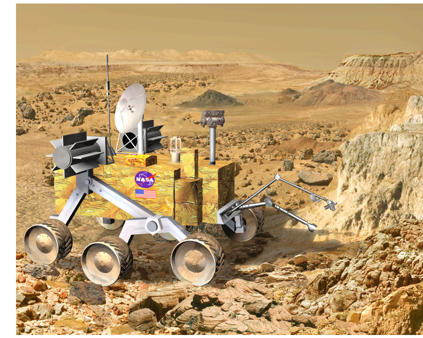
Multiple Repeated Measurements

Orbiters and Rovers



Lunar Prospector

NASA ASTEP Science on the Fly



MSL

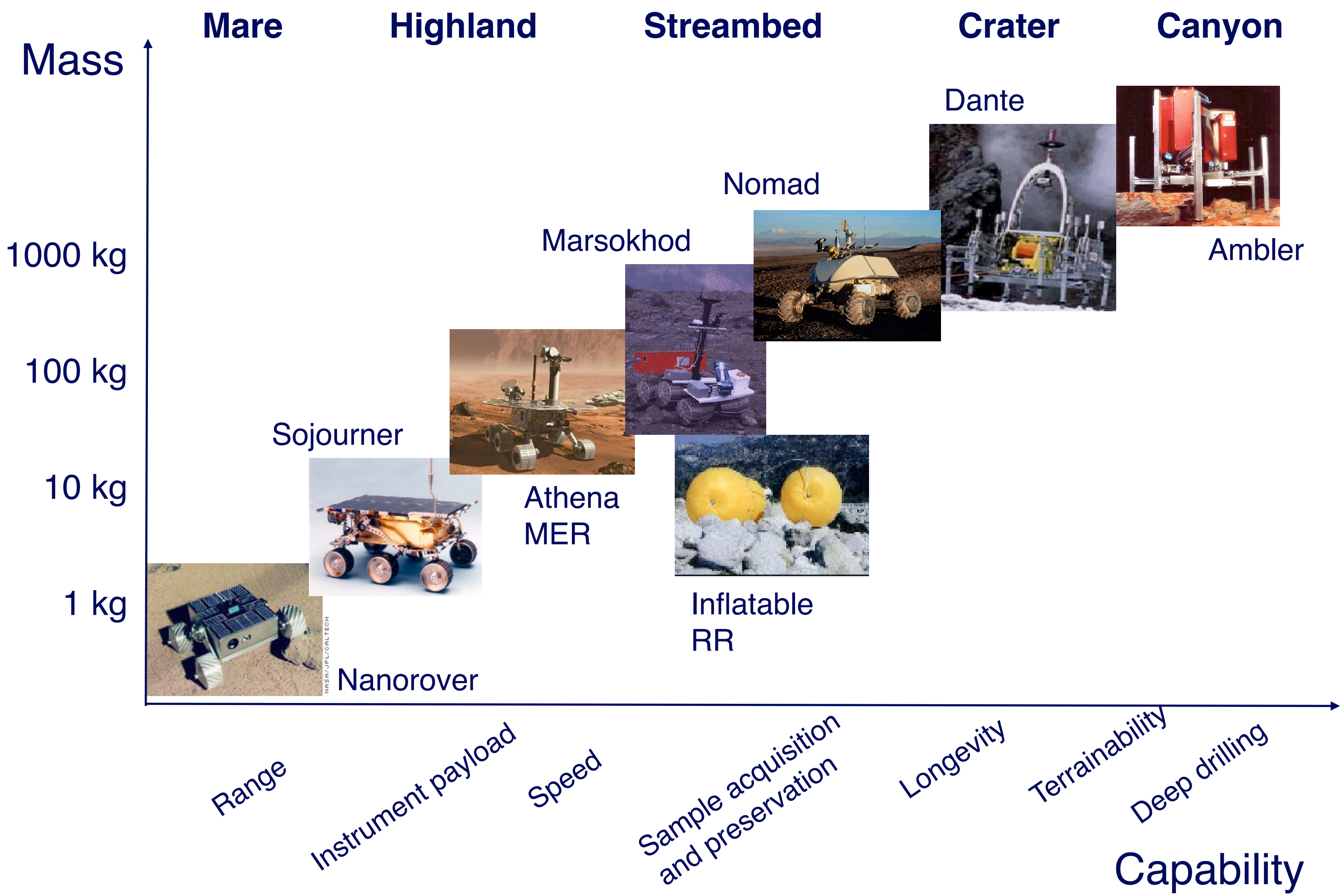
Comprehensive Science Missions

Global Exploration

Regional, Seasonal Measurements

Long-duration Orbiters and Rovers

Increasing Capability



Taxonomy

Exploration Strategy

Sample Selection Criteria

Sample Detection

Sample Acquisition

Data Validation

Data Verification

Science Analysis

Science Interpretation

Science Discovery

Increasing Complexity

Taxonomy

Exploration Strategy	**Static survey, fixed coverage pattern (grid, spiral, random)** **Dynamic survey, variable coverage pattern, feature following** **Directed search, feature-based** **Opportunistic observation** **Opportunistic investigation**
Sample Selection Criteria	**Inquiry-independent (fixed by non-science constraints)** **Inquiry-nonspecific** **Pattern scientist specified** **Pattern derived from scene (automatic classification)** **Pattern generated (autonomous inquiry)**
Sample Detection	**Select search area** **Identify pattern** **Reach position/time/survey constraint** **Evaluate detection likelihood**
Sample Acquisition	**Sample localization/feature tracking** **Sample approach** **Instrument deployment** **Sample collection** **Sample processing** **Sample curation** **Sample disposal**
Data Validation	**Calibrate sensors** **Data quality assurance** **Dynamic range and sensitivity of measurements**
Data Verification	**Effective experimental procedure** **Clear sample naming convention** **Comparison to sample specification** **Correct feature likelihood**
Science Analysis	**Filtering/enhancement** **Data reduction (eliminating data)** **Data compression** **Statistical analysis: categorize, diversity, priority**
Science Interpretation	**Feature detection** **Sample classification** **Probabilistic analysis**
Science Discovery	**Distinguish uniqueness** **Evaluate significance** **Generate Hypothesis**

Extra Robots

Volcanic Gas Measurement

Goal: **Measure gasses to determine activity, distribution and concentration**

Challenges

Locomotion: dexterity in extreme terrain

Dante

Behavior: sensing and adapting to terrain

Interface: conveying status to scientists

Geologic Measurement and Sampling

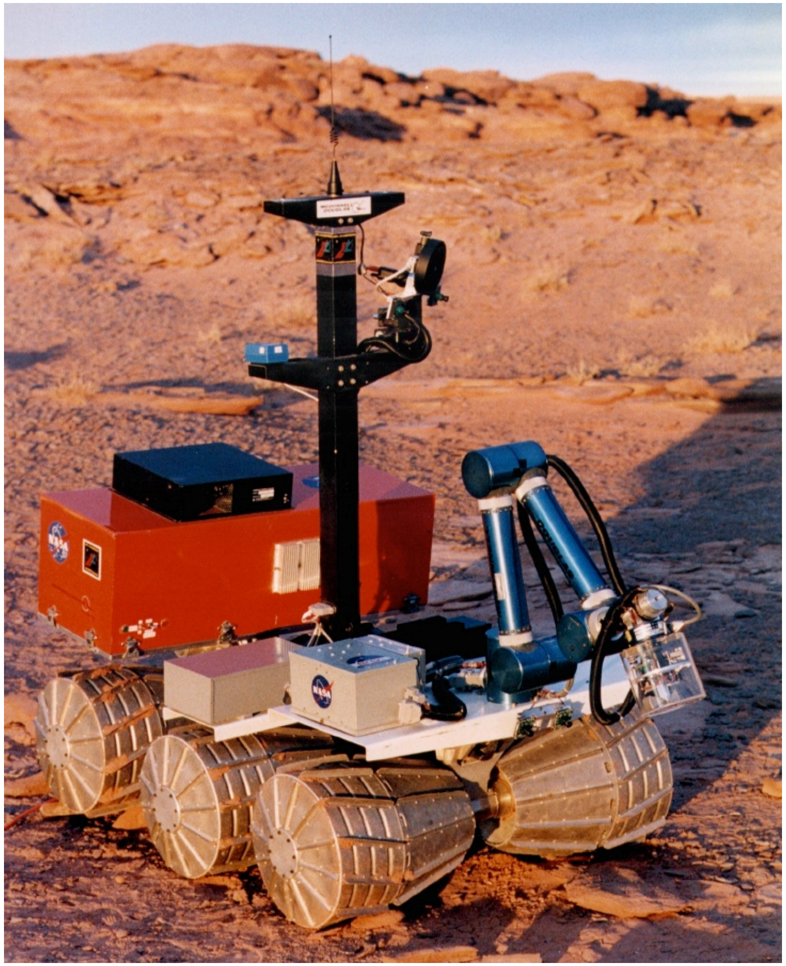
Goal: **Autonomous geological sampling**

Challenges

Autonomy: minimize command cycles

Visual servoing: changing appearance of target

Reliability: knowing when it is not working

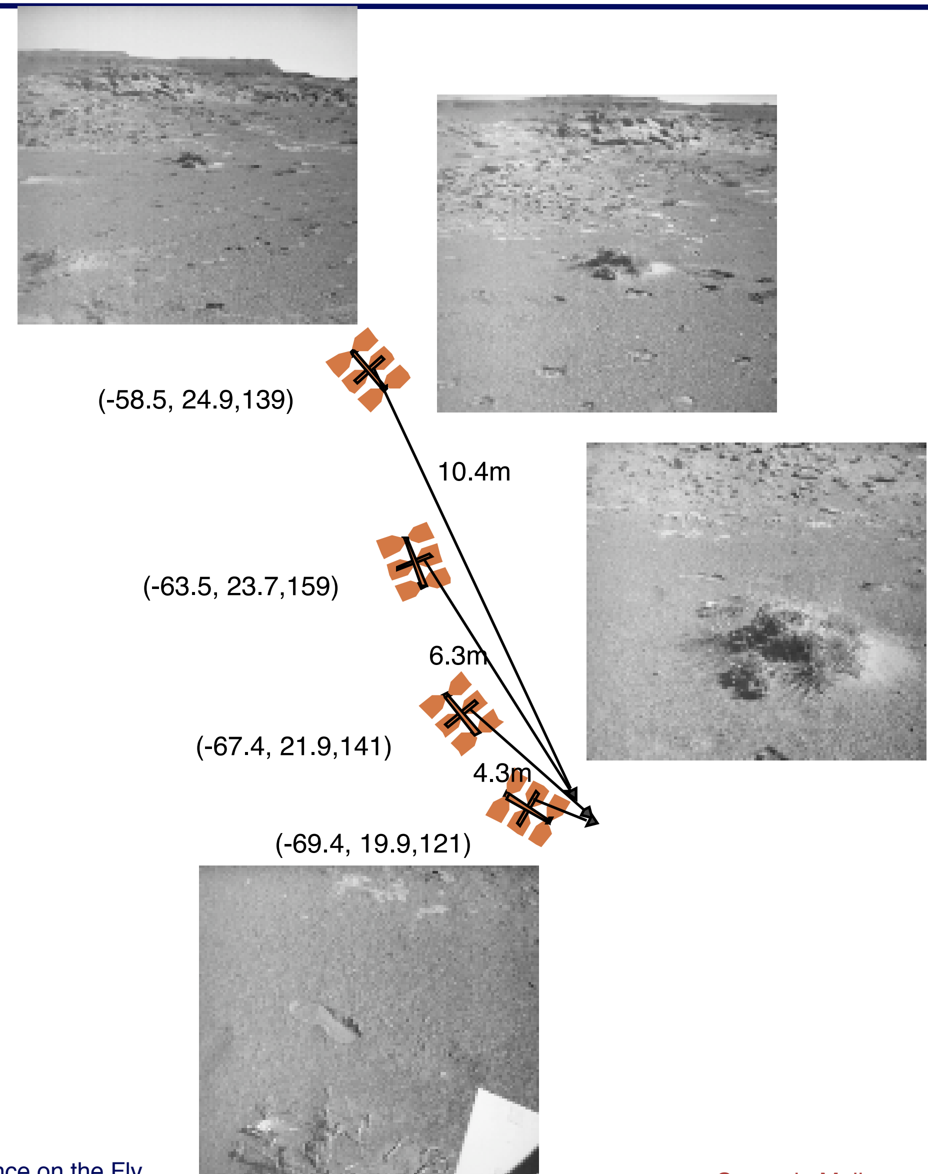


Marsokhod

Autonomous Target Approach

Visual-servoing as autonomous behavior for data acquisition

- ***Motion correlator*** **compares left image with prior template to determine target direction**
- **Motion correlation drives fast pan-tilt**
- ***Range correlator*** **compares left and right images to determine pixel disparity and range to target**
- **Range and motion correlation provide input for robot heading and velocity (guidance)**



Regional Geologic Characterization

Goal: **Long-distance desert exploration**

Challenges

Communication: limited bandwidth

Duration: practice of sustained operation

Nomad

Detection: sensing fidelity capable of scientific discovery

Long-duration Exploration

Goal: **Robotic navigation with reasoning about resources for sustained exploration**

- **Perpetual operation through balancing with power generation and consumption**

Long-Duration Exploration Experiment

Power

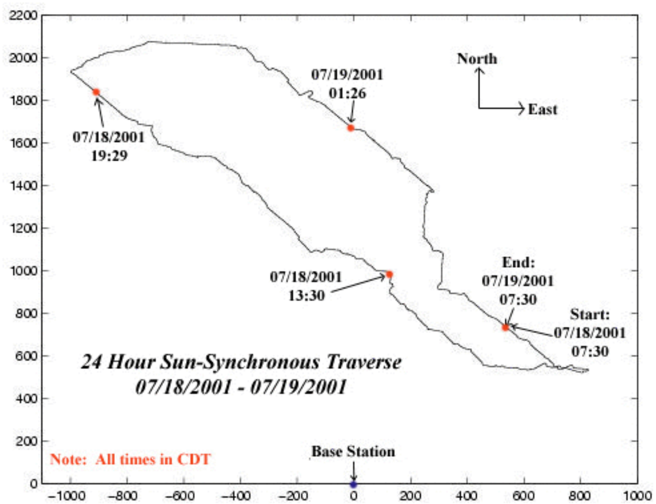
- **Followed resource profile and schedule to complete traverse with batteries fully charged**

Terrain

- **7% (max 34%) obstacle density**

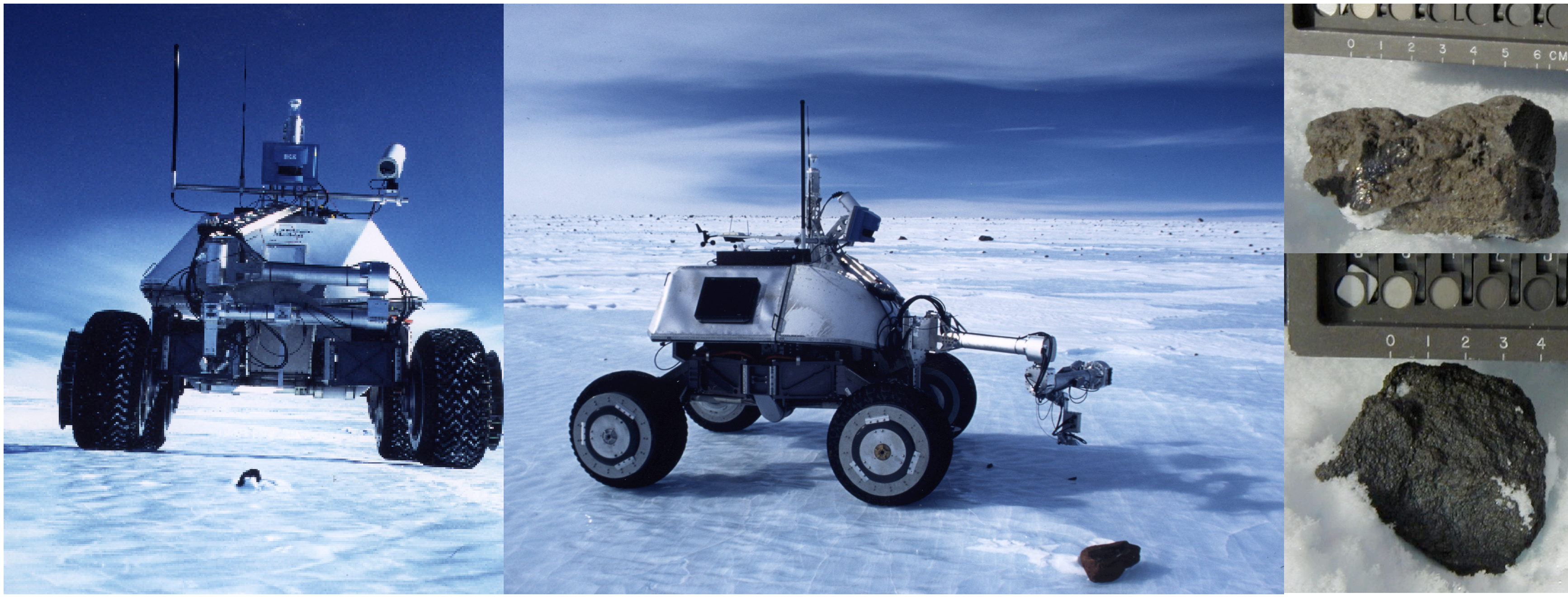
Operation

- **6.1km, No faults, Autonomy 90%**
- **9.1km, One fault, Autonomy 50%**



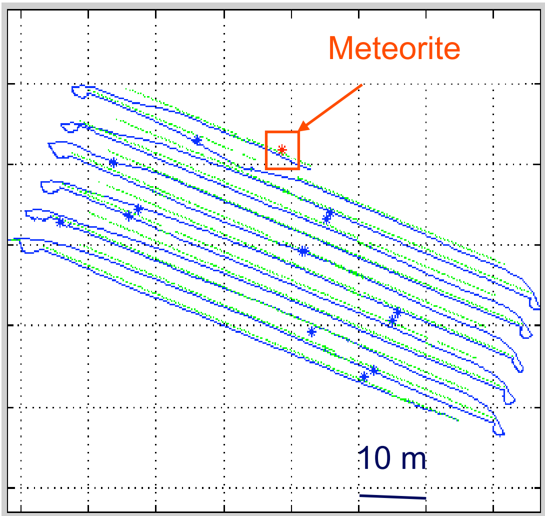
Hyperion on Devon Island, Canada

Antarctic Meteorite Search



Goal: **Automatic detection and classification of rocks on stranding surfaces in the Antarctic where meteorites tend to concentrate**

Rock Detection and Classification

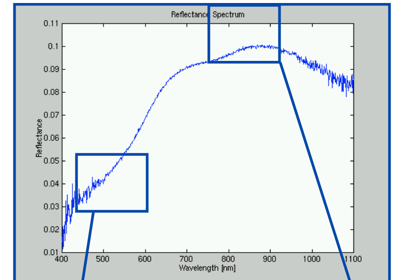


Patterned Search

Hi-res Color Image

Size · Shape · Color

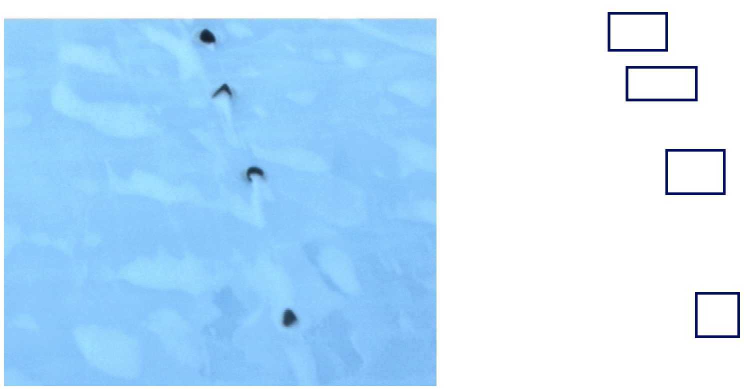
Target Classification



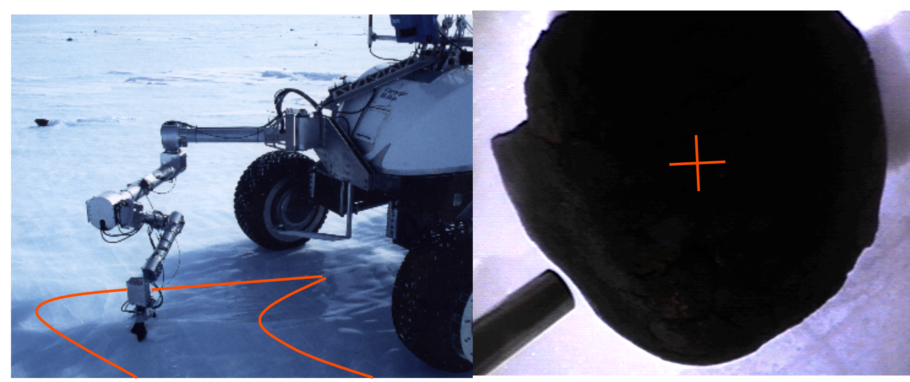
Spectral Feature

...

Spectral Feature



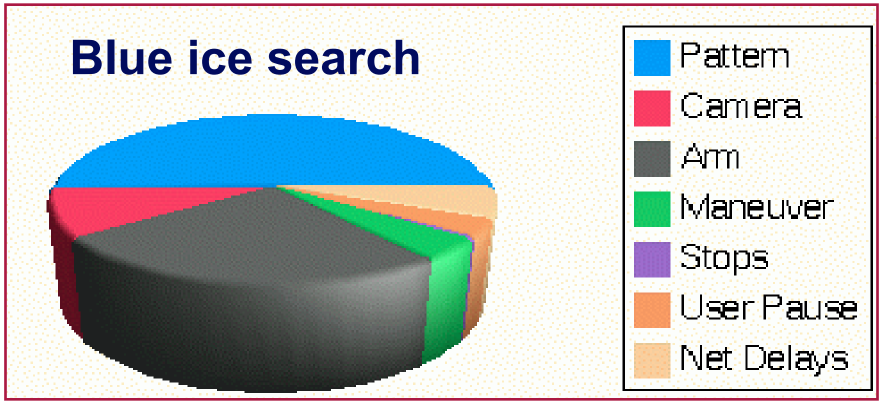
Target Acquisition

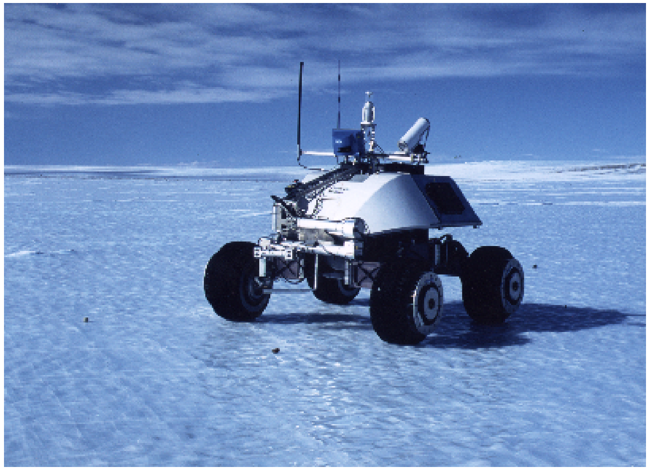


Visual Servoing of Instruments

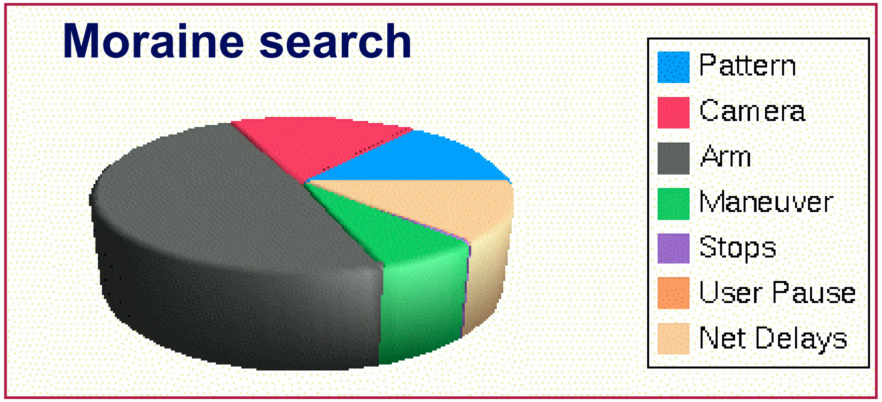
Meteorite Discovery

2500 m^2 searched in 16 hours, 42 samples classified





1 rock / 10 m^2, time to target: 45 min



1-2 rocks / m^2, time to target: 16 min